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FAIRCHILD SPACE AND DEFENSE SYSTEMS
A Division of Fairchild Camera and Instrument Corporation
300 Robbins Lane, Syosset, N.Y.

SCIENTIFIC OBJECTIVES, CAPABILITIES AND CALIBRATION REQUIREMENTS OF THE SURVEYOR S/C TV CAMERA SYSTEM

FINAL ENGINEERING REPORT

30 April, 1965

FINAL REPORT NO. SME-BA-145

JPL Contract 950665

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Approved by: R. S. Brandt
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SECTION 1

INTRODUCTION

1.1 GENERAL

This report is compiled by the Fairchild Space and Defense System Division of the Fairchild Camera and Instrument Corporation in conformance with JPL Contract No. 950665. It is identified as the "Final Engineering Report" for the Scientific and Photogrammetric Objectives and Limitations of the Surveyor S/C TV System.

This report and its referenced appendices are limited to consideration of photogrammetric and photometric objectives and capabilities in the context of providing assistance to JPL scientists and engineers and in the furtherance of their overall task to establish performance requirements for the Surveyor Lander Spacecraft and its associated TV data. In this context, the report is qualitative, rather than quantitative. The analyses conducted and herein reported have been controlled by "best estimates" of prevailing parameters. As such, the report indicates the domain of the feasible and the range of conditions that should be met in order to accomplish feasible goals. Consequently, the report gives an overall perspective on generic uses for the Surveyor Lander TV system, but it does not forecast all of the possible results that would be attained.

1.2 PURPOSE OF THE FINAL REPORT

The intent of this report is to summarize the results of the following tasks:

-- Development of cartographic objectives of the Surveyor S/C TV System.

-- Development of the photometric and colorimetric objectives of the Surveyor S/C TV System.

-- Development of the cartographic capabilities of the Surveyor S/C TV System.

-- Development of the photometric and colorimetric capabilities of the Surveyor S/C TV System.

-- Development of the photogrammetric objectives of the Surveyor S/C TV System.

In addition, this report contains appendices which reference the Fairchild documents developed for JPL which pertain to the details of the material summarized in this report. When applicable, the sections and subsections are cross-indexed to the appendices so that one can delve more deeply into the areas summarized herein.

1.3 ORGANIZATION OF THE REPORT

This report is divided into seven sections, of which this Introductory Section is the first. In the remaining sections the various aspects of this report are discussed in the following order:

1. Overall discussion and recommendations of the scientific objectives and limitations,

2. Summary of the cartographic objectives,

3. Summary of the photometric and colorimetric objectives,

4. Summary of the cartographic capabilities,

5. Summary of the photometric and colorimetric capabilities and,

6. Summary of the calibration requirements and procedures

of the Surveyor S/C TV Camera System.

Related and additional material which is considered too detailed to be included in this report are referenced in the appendices.

SECTION 2

SCIENTIFIC OBJECTIVES AND CONSTRAINTS

2.1 OVERALL DISCUSSION OF SCIENTIFIC OBJECTIVES AND CONSTRAINTS

The fundamental objective of Surveyor Lander visual or photographic observation of the lunar surface is to use the information, specifically, for the extension of scientific knowledge about the moon and solar system. In either case, it is necessary to know "what is there", and "where it is", because we desire to use these observations for the support of some practical activity. Accordingly, the objectives for Surveyor Lander TV data are related to applications which require "what" and "where" information related to areas on the lunar surface.

Data which will be collected by the TV sensor is, essentially, geometric and photometric in nature. From the intrinsic image qualities one can identify and depict lunar surface features as to their shape, orientation, position and reflectance per unit area. It is the geometric characteristic of the information that results in its extension utility. For example, if one desires to evaluate the geological structure of any region, one needs a good map on which the various land forms can be shown. Moreover, if one desires to represent the distribution of photometric properties of any other natural phenomena, it is essential to construct a reliable map to show their distribution. Thus, it is evident that the Surveyor TV data must provide geometric data which, if properly controlled, will reveal the spatial arrangement of features and their photometric properties on the surface of the moon.

Initially, the objective of the Surveyor TV system is to obtain detailed information which would be useful for answering questions about lunar surface qualities in those regions having the highest probability of becoming lunar landing sites. The qualities of the surface which initially must be determined are spatial in form, such as, size, shape, distance, proportion and equality. In addition, one must investigate in relation to geometric qualities, the bearing properties of the surface. These secondary properties to some degree may be inferred from the photometric, colorimetric TV data, and the TV observed Soil Analysis Experiments aboard the spacecraft. Consequently, to provide the information sought from the TV data collected, one must construct photogrammetric, photometric and colimetric models which are quantitative representations of the surface areas observed.

It is apparent that one important performance criterion for any system which seeks to establish surface properties on the moon, must be related to the fidelity of the models that can be constructed from the observations. Moreover, since the general characteristics of the lunar surface or the objects on it are tri-dimensional, the lunar surface can only be described or determined from a point outside by the use of three coordinates in space. This means, of course, that the reconstructed scale models must be tri-dimensional if they are to yield the greatest amount of information. Additionally, to achieve reliability, the models must be accurate and must possess a high degree of continuity. Therefore, important criteria for the Surveyor TV data relates to overall tri-dimensional fidelity and to surface continuity for the mathematical, physical and graphical models which are developed from the observations.

Apart from the general notion that the moon is a tri-axial body and spheroidal in shape, the lunar crust has billions of irregularities covering a range of approximately 7500 meters between so-called lunar highlands and lunar lowlands. Consequently, topographic detail should be plentiful on the moon. From telescopic observations, however, the lunar surface is obscured under full illumination and, even along the terminator, many observations at different phases must be made to sense the detail tri-dimensional form of the surface. As a result, existing astronomical observations are deficient, then, one might establish useful performance criteria for improving upon the existing observations of the moon.

Existing observations from earth are deficient in two ways. First, the resolution is too low to detect all the information desired. Second, the observations are taken mostly from the same perspective point. Therefore, Surveyor Lander observations in the vicinity of the moon, either from descent photos or on the moon from Lander photos, offer numerous possibilities to reduce both of the existing topographic deficiencies in lunar observations.

With respect to resolution, lunar orbiter observations will decrease the distance between earth and moon from 385,000 kilometers to less than 1600 kilometers in the descent phase and less than 2 kilometers after landing. Not only do Surveyor S/C observations provide greater resolution, due to proximity, but additionally, they permit stereoscopic interpretation and evaluation of the surface observed. Translating the increased resolution to information density this means that one can collect, by many magnitudes, more surface information per unit area than is now available through telescopic observation from earth. Obviously, observations in close proximity to the moon imposes more minute considerations about the intricate spatial characteristics of the surface just as one might be concerned with the difference between microscopic and macroscopic observation of any surface. Moreover, now that one may observe "microscopic" lunar characteristics, it is even more important to provide for the best means to reconstruct the "true" spatial arrangement if the observations are to be most useful.

Topographic reconnaissance on the earth usually requires stereoscopic recording of the terrestial landscape, even though knowledge of earth landforms is considerably greater than knowledge of lunar surface forms. For example, features sculptured by running water, which are so prominent on earth, are non existent on the moon. Admittedly, some earth topographic and geologic criteria may be useful on the moon but, surely, lunar topographic and geologic criteria must be developed solely from lunar observations.

It will be known that interpreting images requires the association of a set of clues or suggestive stimuli which permit the perception of real objects as they exist in tri-dimensional space. A two dimensional recording of things distributed in space does not reveal spatial (solid) form by itself. However, it usually offers some hints which permit recognition of the form of objects by way of deduction, e.g., form shadows, differences in reflectivity, relative size and texture of detail. Despite these hints, a two dimensional recording is frequently ambiguous and accordingly it requires expert evaluation to minimize ambiguous inferences.

A three dimensional recording from two perspective views of the same area has numerous intrinsic interpretation advantages. First, it provides a means to suppress or eliminate random noise. Second, it permits the determination of spatial form, directly, from a stereoscopic impression. For example, in stereo vision, the sometimes dubious deduction of spatial form from accidental hints is replaced completely by an immediate sensorial perception of tri-dimensional form, requiring no further mental processes. The sensorial immediacy of stereoscopic form perception is so strong that it leaves no doubt about the spatial arrangement that exists. It is important to recognize however, that the visual stereoscopic model may be identical with a real object or it may be distorted. Therefore, in order to establish quantitative connections between images and events in object space, calibration and control of the acquisition and data handling devices is a prime requisite for the Surveyor TV System.

In summary, it is evident that increased knowledge of the lunar surface can be provided by the Surveyor TV System, if it is utilized as a measuring device. At every step, therefore, Surveyor operational procedures and apparatus must employ the most rigorous and most advanced techniques of reliable measurement.

2.2 SUMMARY OF PHOTOGRAMMETRIC OBJECTIVES

2.2.1 Photogrammetric Type Inputs

The photogrammetric type inputs realized from the Surveyor S/C TV System and utilized to produce cartographic products can be subdivided into the following basic categories:

-- Descent Observations
-- Surface Survey Observations
-- Camera Calibration Data
-- Camera Interior and Exterior Orientation Data

The various processes for assuring the preservation of the data, as well as the photogrammetric transformation and task required to reduce the input, are discussed in detail in Appendix A, Section 2.1.1.1.

2.2.2 Photogrammetric Type Products

The cartographic type products can be itemized according to Descent and Surface Survey Observations.

a. Descent Observations - Cartographic Type Products

-- Topographic Maps
-- Mosaics
-- Three-Dimensional Surface Models
-- Interpretation Overlays
-- Master Site Control Point Network

b. Surface Survey - Topographic Type Products

-- Digital Surface Maps
-- Form - Line or Approximate Contour Maps
-- Photo Maps
-- Three Dimensional Models

The detailed description of the above itemized product and their suggested use are detailed in Appendix A, Section 2.1.2.

2.2.3 Photogrammetric Accuracies and Goals

Photogrammetric accuracy in either the wide angle or narrow angle mode is highly dependent upon two factors.

-- Observation Acuity
-- Calibration Precision

Observation acuity is fixed by the intrinsic characteristics of the camera system and the variations of the perspective conditions over the recorded scene. Calibration precision is obtained by prior measurement of each element in the image recording process and utilization of these data to satisfy the basic geometric assumptions of point perspective views. It should be the major design goal of lunar television recording media to permit exact recovery of the optical perspective conditions which illuminate the vidicon plane.

In addition to the inner orientation controls required for reconstruction of the perspective bundles, exterior orientation must be established on the spacecraft. Since no knowledge of lunar object space will exist, the base distance between cameras should be known with a certainty proportionate to the resolution of the cameras. For the narrow angle case, the base should be known to 1 part in 6,000 for control of the scale factor used in transforming image space measurement to object space coordinates. In addition to the requirements for scale determination, the need for tilt data to control absolute orientation is also established. Two parameters of the tilt should be known.

2.2.4 Time Available for Reduction of Photogrammetric Data

Utilization of photogrammetric data to establish on line focus control is the only activity where "time" is critical in the TV processing chain. The capability to accept TV frames, establish stereoscopic models and quickly measure distances in the object space must be established to permit the verification of focus settings. Since the TV input rate is, nominally, 3.6 seconds per frame, a very high speed capability is required in order to sample at least 1 of 3 frame sets in a single device. Computer routines also must be developed to accept the output measurement of each device and transform the measurement to the focus setting which optimizes the infocus coverage for each TV frame.

2.3 SUMMARY OF PHOTOMETRIC AND COLIMETRIC OBJECTIVES

The mission of the Surveyor Lander S/C may be formulated essentially as: the soft landing of a package of scientific instruments on the lunar surface in an effort to determine some of the basic properties of the lunar surface.

These basic properties include:

-- The spatial shape of the lunar surface about the S/C.

-- The absolute and relative brightness, and color of the segment of the lunar surface before measurement of surface bearing strength and shear strength.

-- The absolute and relative brightness and color of the segment of the lunar surface before and after disturbance by the Surface Sampler.

- The absolute and relative brightness and color of the lunar surface in the area surrounding the spacecraft (allowing measurements associated with Sample Processor and Soil Properties Measuring Device to be inferred to this extended area by photometric and colorimetric and colorimetric similarity).

These local brightness and color characteristics of the lunar surface are to be established by the S/C Survey TV Subsystem. However, it is important to note that in operating the TV, the primary requirement as established in Reports, "Functional Specification, Surveyor Scientific Instrument, Television Experiment 542/43-4-260B" and Conference Report, "Television Experiment Scientific Objectives, Report No. 325-15" (5/25/63), has been for geometric fidelity; photometry and colorimetry following in the order of importance.

2.3.1 Measuring of Lunar Surface Brightness and Color

The following discussion is broken down into two basic aspects; consideration of the lunar surface and the illumination falling upon it, and the effects of a perspective sensor.

a. Surface Considerations

The properties of the photometric function for a non-Lambertian surface indicate that in the case where small increments of the lunar surface (e.g., 1 sq. cm) exhibit the same property, the luminance of that increment will be dependent upon the angle with respect to normal from which the sensor views the object.

The photometric functions which describe non-Lambertian surfaces have important consequences for the measurement of the luminance of the lunar surface from the Surveyor Lander S/C. For objects on the lunar surface which subtend the minimum element of measure on the image plane of the detector ($\approx$ 20TV lines), the angle of emittance of luminous flux with respect to the normal of the surface and each of the survey TV camera remains constant.

Thus, for each of the survey TV Cameras, the domain of the photometric functions is defined over a maximum possible range of:

$$0° < i < 90°$$

$$0° < g < 180°$$

$$\epsilon = \text{constant}$$

where

i = the angle of incidence of luminous flux with respect to the surface normal.

g = the phase angle (the angle between the incident and emitted luminance flux).

The direct implication of this relationship is, of course, that the absolute brightness of such individual non-Lambertian objects on the lunar surface areas which extend over more than one minimum element of measure on the image plane of the detector, it will be possible to establish a value of ϵ for each such element. In the limiting case where a surface of constant $\emptyset$ extend over the entire area about the S/C and is orthogonal to the S/C Z axis, the maximum range of ϵ is:

$$30° < \epsilon < 90°$$

In the case where identical objects are scattered over the area about the S/C, it is possible that a discrete range of values of ϵ will be obtained (one value for each object). It should be noted also that for a S/C landing about 16 days from terminator that the angle of incidence (i) will cover half its range of value (for an orthogonal axis with respect to the S/C Z axis).

In addition, the luminous energy (E) will vary as the distance of the Moon from the Sun changes. But of more importance, the existence of a micro "atmosphere" above the lunar surface will introduce an attenuation factor (τ) reducing the value of E incident on the surface and which possibly may create selective attenuation of the various wavelengths and cause an error in colorimetric measurement.

A more detailed discussion and development of the relationships for measuring the surface brightness is indicated in Appendix A, Section 2.2.2.

b. Perspective Sensor Considerations

Except for a very unusual spatial orientation, the scale of the image on the surface of the TV vidicon will continuously vary over any particular scene. Severe scale variations will occur, particularly, in those photographs which include the horizon. The surface resolution (the dimension on the lunar surface corresponding to the minimum measurable element on the focal plane) will vary with scale. It will also vary to a lesser degree, from focus depending whether or not the object lies outside the depth of field planes.

This variation in image-object size relationship within the photograph has the effect of integrating the information in the minimal unit of measurement. Thus, it is possible to have equal measures of brightness on the detector image plane for two objects which in reality are not equally bright. This effect can occur due to summation of dissimilar luminances into the same minimal measurement area on the detector surface. The size of the minimal unit of measurement on the detector surface must be such as to make adequate provision for errors in sensor orientation with respect to the object as well as provision for dynamic shift within the sensor itself.

Additional discussion on the determination and measurement of exposure as related to perspective sensor considerations are found in Appendix A, paragraph 2.2.2.2.

c. Photometric Inference Between Dissimilar Lunar Surface Areas

Before concluding these considerations of the spectral brightness properties of the lunar surface, brief consideration of the assumptions which are implicit in attempting to extend the results of soil experiments from one area of the lunar surface to another by photometric (colorimetric) similarity must be made.

The assumptions which should be noted as developed in Appendix A, paragraph 2.2.2.3 as implicit in the conceptual frame work are:

-- The effect of the angle of emittance ϵ is so small as not to significantly affect the measurement of albedo of the object (ρ).

-- Dissimilar lunar objects do not possess similar photometric (colorimetric) properties. Thus, if:

A: Lunar Object
B: Photometric Properties

$$A \Longrightarrow B$$

then

$$B \Longrightarrow A$$

It is only in the case where the above assumptions are "reasonably" true that the results of experiments performed on one area of the lunar surface can be inferred to another area by photometric (colorimetric) measurement.

2.3.2 Design and Calibration Objectives for Photometric and Colorimetric Data

The calibration objectives of the S/C TV System related to photometric and colorimetric data are based upon an idealized system as described in the block diagrams and description in Section 2.2.3 of Appendix A.

The factors in the S/C which affect the photometric and colorimetric measurements are as follows:

- -- Source and Scene
- -- Test Patterns
- -- Taking Filters
- -- Vidicon
- -- Temperature Stability
- -- Signal-to-Noise Ratio
- -- Amplitude or Video and Persistency

Detailed discussion of the above factors are delineated in Appendix A, paragraph 2.2.3.1.

In order to determine whether the TV, the signal processing and display system as a unit is yielding a correct and full set of information, a complete calibration of the cameras and data handling systems must be made prior to launch.

The desired calibration for the Surveyor System should be made in three parts:

1. Pre-flight calibration of the ground by impressing known signals into the system at, a) the output of the receiver, b) at the output of the video amplifier, and c) at the output of the vidicon; proper adjustments may be made on the S/C components as well as the reproducing system.

2. Pre-flight calibration of the lens and vidicon by reproducing known objects (test patterns, buildings, etc.) with the best fidelity possible.

3. Pre-flight calibration consisting of the same operations as indicated in 1 and 2 except that adjustment should be confined to using the controls which will be available to the ground when the S/C has landed.

4. Post Landing - repeat of procedure (3) above.

The details of the calibration are shown in Appendix A, Paragraph 2.2.3.2.

2.3.3 Objectives to be Considered in Operation of the S/C TV to Obtain Photometric and Colorimetric Data

Some of the more paramount photometric (colorimetric) requirements for operation of the S/C are:

-- Minimum time delay between observations of the same object where these observations comprise a single unit of measurement.

-- Maximum accuracy of sensor position relative to the object being measured where successive observations comprise a single unit of measurement.

-- Exploitation of photointerpretation to extend the range of emittance angles (ϵ) for similar structure

-- Calibrated brightness values should be used to the maximum extent possible.

-- The establishment of a measurement dimension in the detector which will give high confidence level that successive photos represent the same object, yet no so large as to detract from the total information presented or to introduce errors in emittance angle (ϵ).

-- The examination of specific highlight or shadow areas of a given lunar scene may require f/numbers which under-expose (or over-expose) the average scene in order to render true photometric representation of these areas which are above (below) the nominal scene brightness range.

-- Excessively bright areas may require extensive erasure before viewing lunar surface areas which are an order of magnitude less bright.

Further considerations on the operation of the S/C TV System to obtain Photogrammetric and Colorimetric data are found in Appendix A, paragraph 2.2.4.

2.3.4 Generation and Use of Chromaticity Coordinates

There exists at least two methods of evaluating the color of an object as seen on the Video Data Handling System; the selection of a particular one depends upon the relative importance of the measurement accuracy and design feasibility. Both procedures will produce results consisting of: a) measure of relative brightness, and b) the chromaticity coordinates of the object. In the calculation of the tristimulus coordinates, the input data (video output) can be derived from two sources and thus determine the procedure used. In the first case, the colorimetric information is derived from the video signals stored on the magnetic tape.

Appendix A, paragraph 2.2.5.1 contains a detailed discussion of the first case as well as a discussion of chromaticity, luminance, purity and electronic signal evaluation.

2.3.4.1 Other Measures of Color

As a direct consequence of representing any color in terms of its chromaticity coordinates, an entire set of useful information may be derived. The computed quantities (from the tristimulus measurement) which are of major interest are:

1. Chromaticity coordinates of a uniform-chromaticness-scale, α , β , used to specify changes in chromaticness of a substance with time, exposure, etc..

2. The amount of color difference, ΔE - used to measure color change resulting from treatment of the sample and to measure color differences between two surface colors.

3. The hue angle, saturation index and lightness index.

4. The whiteness of a surface relative to a peak value of 1.00 for Magnesium Oxide and a black surface value of zero.

5. Degree of yellowness in a near white surface.

2.3.5 Methods and Objectives for Graphical Data Presentation

It is possible to satisfy the objective of presenting selected objects and small lunar surface areas about the S/C in terms of differential photometric values by the means of compensated perspective photometric presentations. These can be both binocular and stereoscopic.

These presentations are essentially views of specific lunar surface X, Y, Z coordinates in the orientation of taking camera (similar tilt and swing angles) in which the densities presented have been corrected for:

-- Actual F/Number (I/D)
-- Lens Transmission Loss (T)
-- Exposure Time (Δt)
-- Vidicon, CRT and Film Gamma γ (Q)
-- Electronic Calibration in Transmission and Recording (Δe)
-- Optical and Mirror Vignetting ($Cos^4 \alpha$)
-- Differences Between Actual and Calibrated Brightness (ΔB)
-- In case of Stereo-Correction for Differential Interior Orientation of the Taking Cameras.
-- The Luminous Flex Normal to the Surface (E).
-- The Spectral Distribution of this Flux (λ)
-- The Albedo of the Surface (ρ)

As a result of these corrections the presentation will only vary as a function of:

-- The Angle of Incidence (i)
-- The Phase Angle (g)

However, each individual view will be for a constant value of:

-- The Angle of Emittance (ϵ)

In the case where the same object is viewed in a two camera stereo presentation, it may be possible (depending upon the range of variables involved) to compensate for all the above variables except those of:

-- Phase Angle (g)
-- Angle of Emittance (ϵ)

The effect of the variables of emittance angle (ε) in the photometric function (Ø) between the perspectives of two cameras will provide two values of (ε). Extension to other areas about the S/C can be accomplished by photogrammetric and photointerpretation means to further extend the range of values of emittance angle. Combined graphical presentation of perspective photo view of selected objects and photometric and/or chromaticity values can be accomplished by conventional means.

The use of overlays to a particular topographic map scale presents certain problems which should be recognized. Due to the small height of the S/C TV camera above the datum plane, a large amount of tilt will be present in most views. This tilt in the presence of any surface relief, (particularly relief about the datum) will present a perspective view of the sides of the objects. Attempts to remove tilt, change scale, and to remove relief displacement will have the effect of compression of information on the overlay presentation. As an example, a wall when viewed from the side presents considerable detail, but when compressed into a vertical map presentation becomes a single line when the details of the side are lost.

SECTION 3

3.0 SUMMARY OF PHOTOGRAMMETRIC, PHOTOMETRIC AND COLORIMETRIC CAPABILITIES

3.1 PHOTOGRAMMETRIC CAPABILITIES

3.1.1 Purpose and Methodology of Error Analysis

The purpose of this analysis is to provide estimates of the degree of fidelity with which lunar surface models may be constructed from Surveyor Lander stereo photography. Essential to this analysis is the derivation of the equations from which the coordinates of the photographed object may be computed -- the so-called intersection equations.

The analysis is limited to the area immediately surrounding the Surveyor spacecraft which is observed by the TV survey cameras on the lunar surface. The descent phase is specifically not included here. Further, the analysis only considers the capability of the cameras to map in the spacecraft coordinate system. No investigation of the effects of errors in spacecraft absolute position and orientation is made. Such errors affect the ability to tie local models into a larger network but they do not affect construction of the models themselves. The reason for such a limitation is not essential but, rather, is only to make the task manageable and still satisfy the basic objective, viz., to estimate the fidelity of photogrammetric lunar models.

After deriving the intersection equations, one has a function which relates the observation parameters to the object point. The function may be linearized by using truncated Taylor expansion. Using this linear approximation, one can determine the effects of small parameter variations on the object point coordinates. In linearized form, the differential is used in the general law of propagation of co-variance, to obtain an estimate of the co-variance matrix of the intersection point from an estimate of the co-variance matrix of the parameters. The parameter co-variance matrix is derived from reasonable estimates of the tolerances of the parameter values. Using one of the statistical measures, to be discussed, one obtains an indication of the expected errors. An IBM 7090 Fortran program is used to perform the calculations required.

The development of the intersection equations and the error analysis along with the partial derivatives are found in Appendix A, Section 3.

3.1.2 Program Parameters

The program parameters can be divided into interior and exterior orientation data. The general category of parameters can be additionally subdivided into variance parameters and independent variables.

A. Interior Orientation Variance Parameters

Interior orientation parameters are, usually, the plate coordinates of the principal point, and the principal distance alone. Slightly more generally one may consider any metric quality which affects the image-object ray in the camera coordinate system as an interior orientation parameter. In this sense, lens distortion and camera TV linearity distortions, as well as the errors contributed by photo coordinate measurement, are parameters of interior orientation.

One special parameter which enters in this way is reseau placement accuracy. The TV reseau is a rectangular arrangement of data which is recorded at the time of exposure. The vidicon plane position of each of these reseau data is calibrated when the camera is constructed.

By measuring the coordinate of the reseau points on the resulting film, it is possible to compensate for most of the linearity and film distortion parameters by fitting the measurement to the calibrated coordinate values.

The estimate of the errors to be expected in the image coordinates (x_i, y_i) must be derived from knowledge of the uncertainties in measurements, reseau placement (calibrated coordinates), lens distortion, and principal point determination.

B. Exterior Orientation Parameters

By exterior orientation is meant the position and orientation of the camera axes with respect to the object space. In the surveyor system these become the position and orientation of the mirror. For the purposes of this investigation the mirror positions have been assumed errorless. The mirror orientations are specified by azimuth and elevation angles.

C. Independent Variables

Before any computation can be done one must have the image plane coordinates of the object point for both cameras. This involves, first, choosing an object point, computing the pointing angles for both cameras and, then, finding the image plate coordinates and corresponding principal distances. Appendix A, Section 3.1.5.4 indicates the ranges of the independent variables as well as the numerical values of the variances.

3.1.3 Results of Computer Runs

The error in position determination, as measured by the square root of the trace of the co-variance matrix has been plotted in polar coordinate in each of the planes as described in Appendix A, Section 3.1.7.1. As is to be expected the errors are smallest when the object point lies on a line perpendicular to the line of centers, but along this line the error increases with distance, since the image object rays become more nearly parallel. Also, as the object point approaches the line of centers the errors increase without bound.

Due to these effects this discussion is limited to the region of greatest accuracy.

In this region, the accumulated effect of the errors is to produce an error of approximately 13% at 10 meters, where the B/D ratio is approximately 0.1.

Graphs and tables appearing in Appendix A indicate the detailed result of the computer runs.

3.1.4 Limitations Imposed on Photogrammetric Objectives

The general scientific objective is the acquisition of quantitative information concerning the spatial distribution of lunar features in the immediate neighborhood of the spacecraft. The most desirable form for the expression of this information is the construction of a site model which should be a faithful representation of the lunar surface, and which should possess continuity and smoothness properties.

The degree of fulfillment of these goals is determined by factors inherent in the Surveyor system construction. Prominent among these are obscuration of the surface to multiple camera coverage either by structural members of the spacecraft or shadows and surface defilade, and accuracy limitations of the measuring equipment. These latter are amplified in the regions of colinearity, with ultimate degradation occurring along the line of centers of the mirrors, in which case there is no stereo coverage. Fidelity of reconstruction of a sizeable object in the region of least accuracy will suffer from shape distortions if mapping of its boundary is undertaken by methods of this investigation.

The foregoing analysis of the surveyor system indicates that significant contributions to the overall error are those due to exterior orientation. In analytic photogrammetry there are many techniques by which relative orientation may be recaptured. Utilizing such techniques would reduce by a considerable degree the discontinuities between computed object points. By performing a network adjustment much improved relative positions would be known, and the problem would then be to tie the local adjusted network into a global coordinate system, the Selenographic.

The ability to construct this tie depends upon knowing selenographic position and orientation of the s/c. This latter, the orientation determination, requires knowledge of the azimuth and tilt of the local vertical s/c coordinates, as well as the azimuth orientation of the s/c with respect to local north.

COMPARISON OF POTENTIAL LUNAR MAPPING ACCURACY WITH GEODETIC ACCURACIES

For a first order geodetic survey distance errors must be kept to 1/25,000th of the length of the measured lines, for second order work 1/10,000th, and for third order 1/5,000th.

The final report on Scientific Objectives (SME-AA-98) states that for the narrow angle case, the base should be known to 1 part in 6,000 ... Therefore, the best that can possibly be done is a third order survey. But of course, the results of the parametric study indicate that the results will be much worse than this, the smallest errors being about 1 part in 1,000.

On the surface of the Earth, relatively large surface features (the continents) can be related only to about ±200 meters (1) because the precise relations of geodetic datums are not known with greater accuracy. Comparing this with similar lunar determinations we may quote Kopal:

"The deficiencies inherent in the present systems of selenographic coordinates (as reflected, e.g., in the Wesley-Blagg I.A.U. "Atlas" 1935) are probably displacing whole lunar regions by several kilometers relative to others; and their uncertainty constitutes also the principal source of error in the determination of the heights of the lunar mountains from the measured lengths of their shadows ..."

The inaccuracies in the determination of Selenographic coordinates and orientation of the spacecraft make it impossible to construct charts comparable to those in use on Earth's surface.

On the other hand, Surveyor scientific objectives will not necessarily be hampered by these absolute inaccuracies because the capability to determine correlation between the physical properties of the surface and its small detail topography. The relatively high resolution photography will also be used to determine the aerial distribution of small impact craters, where their diameters are less than the limit of present telescopic resolution, and will certainly help to answer questions concerning the utilization of men and equipment in lunar exploration activities.

3.2 PHOTOMETRIC - COLORIMETRIC CAPABILITIES

3.2.1 Basic Considerations and Calibration Methods

When considering the limitations imposed upon the photometric objectives of the television experiment by the Surveyor Lander Spacecraft Television Camera System, and the photometry thus achievable, the notion of absolute

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(1) Tesseral Harmonics of the Gravitational Field and Geodetic Datum Shifts Derived from Camera Observation of Satellites Journal of Geophysical Research V68, Jan. 1963, No. 2.

photometric accuracy shall be redefined to apply only as it relates to the TV Camera System.

Absolute photometric measurement in this context then refers to that ability to determine, at the Spacecraft Television Ground Data Handling System, having taken into account the photometric transfer functions of the mirror, the lens, the filters, the shutter and the iris. More simply (and less accurately), it is the ability to determine the luminance of an image area.

By adherence to this definition, the problem of Lambertian versus Non-Lambertian reflection, the desirability of full integration of the surface reflected radiation, and the questions of sun angle, normals, etc., do not (and should not) apply. They are, in fact, little related to the performance of the TV system and, conversely, are not constrained by the TV system, especially if such limitations as the immobility of the landed spacecraft are considered to be external to the TV system. Within the precision of the system, however, it should be possible to determine the reflectance of the lunar landscape in the direction viewed. Both the incident illumination and the luminance shall be calculable to some accuracy.

Considering the input essentially at the focal plane, as defined, absolute photometric accuracy may be obtained in either of, or in a combination of two approaches.

The first is to provide a calibrated subject, post landing, presented to and viewed by the TV camera a short period before or after the survey frame is viewed (to minimize parametric drift). The data obtained from the calibration frame is then used to determine the photometric brightness of the scene by direct comparison.

The existing Spacecraft Television System provides no calibrated source of illumination. Under this constraint, such measurement is predicated upon the knowledge of the magnitude and direction of incident solar illumination upon a test chart mounted on the spacecraft. Such information may be calculated from the known pointing angle of the spacecraft solar panel. The accuracy of this information will, of course, be contingent upon both the accuracy to which the solar panel orientation is known and also the degree to which this panel is pointed for maxima.

The second generic method of obtaining accurate photometric data is to precalibrate prior to launching, the photometric response of the Television Camera System for all expected values and combinations of expected environmental variation and aging, and to know or monitor and telemeter the values of the influencing factors during the mission. Having these sundry calibration functions on hand at the S/C TGDHS, luminance is eventually determined. Even if such a comprehensive monitoring were practicable, only systematic variation could be accounted for, with the others added to the random noise. Another factor not taken into account would be the results of a chance mishap or malfunction occurring between launch and landing which, without making the system inoperable, may permanently and immeasurably affect the precalibration. Examples of such effects are radiation damage changing the response or sensitivity of a component, displacement of an optical or electromagnetic component, and opening or shorting of, for example, a resistor in the video amplifier chain.

Because of the impracticality of the above, several compromises have been made. Certain critical temperatures and calibration voltages of the Television Camera System, which have the major effect upon calibration, are monitored. All other effects are lumped and considered contributory to the reduction of the overall photometric error. Also, one or a number of standard test targets mounted on the spacecraft and illuminated by the sun shall be viewed.

3.2.2 Description of TV Signal

The video signal represents, as a function of time, a voltage analogous to the brightness variations of the original scene, presented line by line in sequence with dead time (blanking or fly-back) between lines. Two levels are defined as black and white and represent the maximum excursion of the signal. The degree to which intermediate levels may be delineated is dependent upon the noise present in the system.

The vertical (orthogonal to a scanned line) size of a picture element is approximately equal to the center to center distance between two scanned lines, centered on each line. Along a scanned line, the horizontal size of a picture element is a function of the spatial or time bandwidth (the amount of information present), as modified by the aperture admittance, and is, in this case roughly equal to the vertical dimension, yielding a square picture element (pixel).

At the S/C a projection of the original three dimensional subject, the lunar terrain viewed, is imaged on the screen of a vidicon TV camera tube by means of a mirror and lens combination. The plane mirror is stepped in elevation and azimuth and serves to direct the camera field of view. The lens has adjustable focus and variable focal length, with a resolution capability considerably greater than that of the television system. In addition, there is an iris to provide exposure control, either commanded or automatic, and a shutter which normally provides a 20 millisecond exposure for the approach TV camera and a 150 millisecond exposure for the survey TV cameras. The image on the screen of the vidicon has a 1:1 aspect ratio and a 5/8" diagonal (approx. 7/16" on a side). The image converted to an electrical signal whose amplitude is a function of the magnitude of the brightness of the original scene (modified by the spectral response of the optical elements, screen, and filters interposed) is raster scanned with the reference sweep direction left to right and top to bottom in the scene when the mirror axis is parallel to the raster and the camera is looking out. The two dimensional scalar field of the image with magnitude as a function of position then becomes an electrical signal with magnitude as a function of time and time parametric to position.

To conserve bandwidth and yet maintain resolution, "slow scan" is utilized. Each frame is scanned in one second with an additional 0.2 seconds for vertical blanking time (primary mode). In normal operation, the maximum picture repetition period is 3.6 seconds (three full scans) to permit two erasures between actual picture transmissions. The system is capable of cycling every 2.4 seconds (one transmitted scan, one erasing scan) but a residual image may result. The raster is 600 times and the line scan rate 600 lines per second. The passband of the video signal is 220 kcps which is adequate to provide horizontal resolution equal to the vertical. To conserve the slow changes in background lighting, clamping is applied. The vertical blanking pulse, horizontal synchronizing pulses, horizontal blanking pulses and ID data are added to the signal providing a composite video signal with blanking at black level, synch peak blacker than black and the ID data during the 2nd vertical blanking gate. This signal modulates an FM transmitter and is transmitted to the DSIF stations.

3.2.2.1 Design Goals of TV System

Upon acquisition of the video information, minimum automatic gain control applied is 27 lb. The demodulator output is positive for an increase in FM frequency. Demodulator phase distortion is less than 0.1 radian over the passband (approximately 6 degrees). Some design goals are: Dynamic range or contrast ratio is 30:1 with 10 levels of grey. Linearity is ±5% known, repeatable and correctable to ±1/2%. Raster drift on the vidicon screen is $\leq$ 5% in any direction. The overall photometric relative accuracy is ±15% of the maximum signal short term and ±20% of the maximum signal over the term. The absolute accuracy related to the original scene brightness is ±30%. The above photometric accuracies refer only to video information below 50 kcps. The overall signal-to-noise ratio is 27 db.

The vertical and horizontal oscillators in the S/C are free running and not co-synchronized. Line synchronizing pulses are transmitted during vertical blanking. S/C transmitter turns on immediately prior to the first blanking gate.

A concept which serves to isolate the photometry of the Surveyor Lander Spacecraft Television Camera System from that of the GDHS should prove useful. The objective shall be to relate the luminous intensity of the lunar surface viewed in the direction viewed with the corresponding value(s) of the luminance (video) signal at the first or most upstream point of the GDHS where such measurement is feasible.

A logical assumption is that the operations necessary at the GDHS to acquire and reduce the received carrier to a baseband video signal (the media form for first photometric measurement) are ideal to the extent that the incoming signal is handled in an optimum and completely predictable manner as would be hoped for and expected at the GDHS.

Such upstream measurement is probably useful only for purpose of calibration of the Surveyor Lander Spacecraft Television Camera System.

For general photometry with a fully calibrated (calibratable) GDHS, the measurements may be made on hard copy photographs and related to the video signal which, in turn, may be referenced to the original scene.

As described earlier, a major photometric functional interface in the Surveyor Lander Spacecraft Television Camera System is the focal plane, the photo-conductive faceplate of the vidicon television camera tube. At this point the luminance of the image may be construed to be the output of an "optical camera". The camera is comprised of the functions, operations and parameters of the mirror, the filter wheel, the imaging lens, the iris and the shutter. The input to the camera is the luminance of the lunar surface in the direction viewed.

The functional blocks of the remainder to the Television System in the direct photometric chain are the vidicon, the video amplifier, the video processor, the modulator, the transmitter and the antenna; and included shall be the signal transmission characteristics to the DSIF. The interface between the spacecraft portion of the television system and the ground data handling portion shall be a plane at the DSIF antenna. The detail of the effect that the GDHS components have on the signal is found in Appendix A, Section 3.2.2.1.

3.2.3 Telecommunication Noise

Analysis, which is detailed in Appendix A, Section 3.2.3, indicates that the S/N ratios as predicted at the telecommunication link will have only a small effect upon the photometric accuracy, i.e., an error of 5%.

3.2.4 Forecast of Relative and Absolute Photometric Accuracy

Insofar as the short term relative photometric accuracy is concerned, noise is the major contributing factor. From the foregoing considerations, it is estimated that the ability in the GDHS to detect small changes in luminance will be about one part in twenty and the short term relative photometric accuracy will be approximately 10%.

Absolute photometric accuracy (as defined herein) while quite dependent upon pre-launch calibrations as discussed, should be ±20% or better.

3.2.5 Photometry Calibration

The photometry phase of measurements of object brightness on the Moon can be related to all three television cameras. The approach camera has a short useful life, and it is capable of providing quantitative photometric measurement of the scene. Only monochrone pictures will be attempted with the approach camera, because of its high velocity and repidly changing subject matter during an approach. There will be insufficient time for re-adjustment of this approach camera during flight but it could be precalibrated in iris setting and in video output level versus brightness of test pattern targets. If it is provided with a photosensor, controller by average scene brightness which then resets the iris to optimum picture performance, then this setting can be interpreted quantitatively into photometric calibration numbers. The video signal amplitudes from reference black level can then give relative brightness of various portions of the scene.

The photometry can be more precisely relied upon from the two cameras operated after landing because there will be time to adjust them for optimum performance. This will be accomplished by suitable command signals and precalibration on the ground and then subsequent check calibration on the Moon by panning one or both cameras so as to view a known, suitably mounted, test target which will have grey scale calibration and geometric information as to resolution, image size and shape. In the calibration of the two survey TV cameras after they have landed on the Moon, use may be made of the pointing angle of the solar cell panel. This solar panel is directed for maximum sunlight pickup and thus determines the landing angle of the Surveyor Spacecraft.

From this can be properly deduced the incident sunlight illumination and its variations with time onto the standard test charts (and on the object space). Knowing reasonably well this incident illumination, then one can derive a quantitatively reliable calibration of the video signal amplitudes in terms of the known reflectivity of the illuminated test charts. This chart or charts can be made optimum for both monochrome and color.

Since many hours may elapse during surveillance television operation, it probably will be desirable to recheck the photometry calibration by viewing the test chart, say, once every two hours so as to detect and take into account possible drifts in electronic equipment performance caused by temperature variations, power supply fluctuations. and other fluctuations, and other variables, as well as the changing of Sun illumination both upon the test patterns and upon the surface surrounding the spacecraft.

3.2.6 Time Sequence Related to Photometry and Colorimetry

Many considerations must be taken into account in the final choice of operational time sequence for the mission. If the cameras are properly pre-calibrated, then the television information can also give photometry data while the primary mission objective, photogrammetry in stereo, is being achieved.

As far as colimetry is concerned, however, the accomplishment of color viewing by television requires insertion of color filters and it is recommended that the color exploration be done with only one of the two stereo TV cameras since it will take considerable time to view the selected areas of the Moon's surface in color. It is understood that there is an interval of plus and minus two days around lunar noon during which time the equipment will probably be too hot to provide dependable performance. Accordingly best color of a given object space could be achieved by allowing one TV camera to point continuously at this object space and then permit a red picture, then a green picture, then a blue picture to be transmitted in a rapid sequence separated only by about 5 seconds from each other. This, however, would not produce the most color pictures of the greatest area in the least time because of the finite-time required to change color filters. Accordingly, if the electronic equipment remains stable in prior ground tests, then the color picture can be taken with one camera taking a whole annulus of adjacent exposures with one color filter left in place for the entire sequence. Then this same camera would have its color filter change, say from red to green, whereupon a second annulus of adjacent exposures would be repeated. Additionally a third ring of exposures would be made using this same camera, but with a blue filter in position. There is, of course, in such a picture taking sequence, a problem of registration of the homologous pictures, consequently, the mechanical resetability of the mirror in azimuth and elevation must be reliable in terms of the 600 line scan system.

3.2.7 Spectral Response

The system will yield far better results if the color filters used are balanced for optimum match with the spectral response characteristic of the vidicon camera tube. It is possible to get color distinction between subjects in the object space using only two color systems. By far more precise colorimetry can be achieved if the three filters are employed, even though it will take longer to transmit three sets of television pictures. The vidicon tube must have a reasonable response in all three regions of the color spectrum; red, blue, and green. The peak response of the vidicon will probably be in the blue region. This is understandable, since the vidicon in achieving its primary assignment of stereoscopic photogrammetry must have good sensitivity and good stability, as well as low noise. Also the vidicon is being choson with capability of performing in the slow scan mode commensurate with the great distance over which the data link must operate and still provide good signal-to-noise through the system. Measurements should be made to determine the overall monochrome response of the vidicon to assure excellent pictures under the ambient light conditions expected from sunlight under the albedo conditions of the Moon object space. This vidicon should, under these operating conditions, also be measured for spectral response, determined by signal output versus reasonable bands of the spectrum starting at the red region and going through the green and into the blue region. If we assume that the checked signal output for monochrome unfiltered optical input is 100 units, then we should expect that the response in any of the three spectral regions is red, green or blue.

Next, the filters should be chosen as to spectral pass characteristics and as to relative dispersion so that the color output signals from known reflected test targets will give output signal voltages which will reasonably fill the video amplifier dynamic range when the color filters are in operation on the television camera. The unknown subject matter of Moon object space will not necessarily reach these maximum levels of brightness to cause full dynamic range video signals in the processing amplifiers, but instead, will probably occur at some reduced levels whose magnitude it is desirable to measure. Simulated tests prior to launch should determine whether expected reduced levels of color signals are adequate in signal-to-noise, through the system chain to provide reliable results and which would justify spending the time in attempting to get colorimetry information from the Moon.

A firm forecast of the percentage accuracy which can be achieved in colorimetry must be based upon the results of equipment measurements prior to flight and measurements made on test targets after the equipment reaches the Moon. If one assumes a system signal-to-noise performance of 30 db for monochrome mode of operation, and there is some reserve iris openings which can be called upon to increase the optical efficiency, then switching to color one can then expect the absorption of the color filter to drop the signal-to-noise at the camera to say 20 db. Such performance will vary, however, with the angle of Sun illumination and other matters which are discussed in more detail later. The stability of the spacecraft circuits will throw some uncertainty into quantitative colorimetry and the further variables in the ground equipment induce more uncertainty as to calibration. Hopefully, it can be expected that with preliminary system testing, it will be possible to determine colorimetry to an accuracy for medium brightness areas of a scene within about 30%. The hue of a portion of this scene is dependent upon the stability of the circuits, the matching of the taking filters and the appropriate registration in the reconstituted color image. Also the hue of a portion of this scene is dependent upon the stability of the circuits, the match of the taking filters and the appropriate registration in the reconstituted color image. Also the hue can be distorted seriously if hangover image storage signals remain on the vidicon from a previous scene. If these variables are controlled or properly compensated for then the geometric plot of an object area can be placed upon the color triangle with a certainty of perhaps plus or minus 20%.

3.2.8 Ground Testing

It is imperative that the Surveyor television system be thoroughly ground tested and calibrated as to photometry and colorimetry. The spacecraft equipment and ground equipment have been outlined in block diagrams in Section 2 and some recommendations as to appropriate calibration tests are treated in that section.

Certain ground tests for calibration purposes should be made by way of alignment equipment with all controls available so as to secure optimum performance. These tests should include synthetic electronic signals such as synchronized pulses, step wedge signals and pulses, simulating a small white area on a black background and pulses simulating a small black area on a white background. With these synthetic signals introduced, transmitter and ground receiver and monitoring equipment can be evaluated and optimized. Clamp circuit performance, particularly, must be optimized if photometry is to be preserved, independent of average brightness distribution in the scene. Another series of ground tests should then be made with test pattern signals introduced through the optical system into the vidicon to determine that scan size and shape is correct, resolving power is proper, focus is appropriate and sensitivity and signal-to-noise is adequate.

Further tests should be carried out with respect to photometry and colorimetry reliability where the controls which are to be available for adjustment from the ground are the only ones receiving further attention and under these conditions tests should be made with appropriately illuminated test targets mounted on the spacecraft and with scenes simulating Moon object space.

In simulation of Moon object space one cannot at the present stage of knowledge provide precise color subject matter but at least some colored matter should be resolvable in the system at relatively low contracts which are to be expected on the Moon.

After the spacecraft has landed on the Moon colorimetry calibration tests should be accomplished with the periscope optical systems of one or both stereo cameras pointing toward color test charts mounted on the spacecraft. It is hoped that appropriate illumination will be available.

3.2.9 Effect of Lighting on Color

The stereo photogrammetry will probably best be achieved looking in all possible directions from the spacecraft, but it will probably be found that observation in color will be most successful with a TV camera looking in the direction away from the Sun. A field of view of perhaps 120° will yield good color results by color television. If shadows have crept into the picture, then, those parts of the scene which are not deep shadows will yield relatively little photon excitation through the additional absorption of the color filters and the color pictures will be quite noisy. It is important that the intensity of the illumination is adequate for good signal-to-noise in the television system, if good color discrimination is to be achieved. This is a further reason to limit the color viewing to the well illuminated areas and avoid wasting the time to attempt televising in directions near to that from which the Sun's rays are coming.

3.2.10 Real Time Color Viewer

Since the color to be expected in the Moon mission is somewhat of an unknown quantity it may be desirable to provide in the ground monitoring equipment a color real time viewing mechanism. If this apparatus can be simple and speedy of operation it can be used to evaluate the initial color television received pictures. Then the subsequent time schedule can be selected with assurance so as to make the most efficient use of this spacecraft capability for either gathering more color information if it is deemed worthwhile, or else modifying the pre-arranged schedules to utilize the spacecraft to accomplish in more detail the efforts of other portions of the mission. The ground recording equipment can yield colorimetric results by use of several types of equipment which is discussed in detail in Appendix A, Section 3.2.10.

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SECTION 4

CALIBRATION REQUIREMENTS AND PROCEDURES OF SURVEYOR S/C TV CAMERA SYSTEM

4.1 GENERAL

The objectives of the task summarized in this section are to assist the JPL Television and Ground Data Handling Cognizant Engineers to establish the evaluation, test and calibration requirements for the Spacecraft Television Camera Subsystem in order to satisfy the photogrammetric objectives of the Surveyor Lander Operational Missions. These tasks include:

a. Reviewing and commenting on specifications submitted by JPL.

b. Attending and reporting on meetings in the capacity of consultant.

c. Writing test procedures.

d. Reducing data to provide calibration constants on lens tests run at JPL.

e. Suggesting tests of cameras and spacecraft relative to alignment. Included also have been suggestions (not necessarily complete or adequately detailed) as to final testing of the spacecraft.

In reviewing the comments on the Specifications and Calibration Procedures which were generated, it is important to note that many of the problems peculiar to this particular photogrammetric task have occurred because the photogrammetric objectives were not defined until after the design and fabrication of the lens and camera had been completed. Standard calibration techniques for this reason have required considerable modification. This is obvious in the testing that has been done to date with the lens alone, and if significant and reliable calibration data is to be obtained with the completed spacecraft, extensive testing of the alignment and performance of optical and electronic elements must be done prior to launch.

The first requirement for photogrammetric equipment is stability under all operating conditions such that the geometric constants derived from calibrating the lens, camera and spacecraft are dependable. It is of primary importance that this operating dependability be proved not only under ambient earth conditions, but for the simulated lunar atmosphere. When dependability has been proved it will be found to be a function of environmental conditions. It is known, for instance, that the spacecraft will be subjected to large changes in temperature. Such conditions must result in dimensional change of the base length between the two cameras, a possible warping of the orientation of one camera with respect to another, and a change in the focal length of the camera lens. These are expected and predictable occurrences. What is photogrametrically important is that the magnitude of the resultant geometric changes be known, and that they be repeatable test after test.

Beginning with the calibration of the lens, a serious consideration is that the vidicon face plate is part of the optical and geometric performance. In testing the lens as a lens, however, it is obviously not possible to use the vidicon tube with its face plate, and a simulated master plate is used instead. Secondly, there is no positive longitudinal or lateral positioning of the face plate such that the lens, as it includes the face plate, is a rigid assembly. These two characteristics can introduce errors both in the optical and geometric performance of the lens.

At the inception of the photogrammetric task it was expected that photogrammetric information would be obtained at any focal length of the variable focal length assembly. The decision to reduce this, such that only the infinity focus of the 100 mm lens, (and possibly the 25 mm lens), will be used, has drastically reduced the problems and made accomplishment of a photogrammetric mission with the present design feasible.

4.2 REVIEW OF CALIBRATION PROCEDURES AND SPECIFICATIONS

During the course of the contract FSDS reviewed and commented on several calibration specifications and procedures. These comments are in Appendix B and are meant solely to serve as guidance in reviewing and rewriting the specifications and procedures. The latter will then serve the purposes for which they were written; (1) to control the quality of the product proving quantitatively its acceptability for the photogrammetric tasks; and (2) for acquiring and reducing physical and geometric data which will establish the geometric and image quality characteristics of the lens or camera.

Appendix B, Section 2, contains comments on the following:

- Bell & Howell presentation of the Variable Focal Length Lens Assembly for Project Surveyor Television.
- Hughes Integrated Test Plan, Phase I.
- Variable Focal Range Lens Assembly
- Finalized Copies of the Type Approval and the Design Evaluation Test Procedures.

- JPL Specifications for "The Surveyor Television Camera Alignment".
- JPL Draft for "Determination of Errors and Statement of Requirements for Aligning of Survey Cameras in Terms of the Photogrammetric Aspects of the Experiments" as of November 19, 1964.

4.3 CALIBRATION SPECIFICATIONS AND PROCEDURES

Calibration Specifications and Procedures have been generated by Fairchild Space and Defense Systems. The details of the specifications and procedures are found in Appendix B, Section 3. The first "Work Plans" were composed of informal directions and sketches written while the JPL lens tests were in progress, and except for the "Calibration Work Plan for Lens X-14 Surveyor Lander" (refer to Appendix B, Section 3.1), they have not been included.

The procedures for Resolution Testing of the Variable Focal Length Lens at finite and infinite distances are techniques which can be visual or photographic and which with slight modifications can be extended to cover testing of the vidicon cameras and the cameras mounted on the spacecraft operating under environmental conditions.

The JPL development of the modified goniometer and the refining of their optical testing techniques has made a well controlled goniometer calibration of the lens feasible. Depending on space considerations, it may also be possible to extend this testing to calibration of the vidicon cameras. In this case, the telescope of the goniometer will be illuminated and the cross hair will be photographed by the vidicon camera. A high quality monitor will display the reseau and the image of the telescope cross hair when the telescope is at a known angular position with respect to the vidicon camera. Exposures taken of the monitor can be processed and measured on a two-coordinate comparator. Data can be reduced in a manner similar to that shown in the tables included in the Goniometer Test Procedure. With the addition of the known dimensions of the vidicon reseau an operational calibration can be performed which is significant of the output of the camera.

Appendix B contains the following Calibration Method and Work Plans:

- Calibration Work Plan for Lens X-14 Surveyor Lander
- Visual and/or Photographic Resolution Testing of the Variable Focal Length Lens and Its Infinity Focus Positions Using an Optional Bench.
- Resolution Testing of the Variable Focal Length Lens Assembly Using Resolution Targets at Finite Distances.
- The Goniometer Method of Calibrating Variable Focal Length Lens Assembly.

4.4 CALIBRATION OF X-14 LENS

Appendix B, Section 4, consists of reports on the calibration of the X-14 lens. These do not include resolution testing. Both tests were limited by the time allotted to the schedule. While not adequate to determine the precision of data of repeated tests, it was adequate to allow the solidification of test procedures and to determine the quality of the modified goniometer equipment.

The results of these two tests show that both the testing method and the test equipment is adequate for obtaining average distortion values and that, while the assymmetric distortion characteristics are informative, their values cannot be transferred to the characteristics of the completed camera, since as shown in the results, they are largely due to tipping.

Appendix B contains a report on the "Calibration of the X-14 Lens" and a report on the "Data Reduction of Distortion Tests Made on the X-14 Variable Focal Length Lens at JPL".

4.5 SUGGESTIONS FOR TESTING COMPLETED VIDICON CAMERAS AND FOR ALIGNMENT OF CAMERAS ON THE SPACECRAFT

One of the most important phases of testing for all photogrammetric cameras is the verifications of cartographic performance of the completely assembled operational camera. For aerial mapping cameras this may require a flight test over ground-surveyed terrain where numerous photo points have been identified and their geologic and topographic positions determined by first order survey. In a Camera Calibration Laboratory it may mean the simple exposing of film in the test camera to the targets of a calibrator--an array of collimator targets at specifically selected angles--and the analytic display of resultant photography on first order plotters. Reduced data or the recovery of surveyed distances and heights determines the acceptability and reliability of cartographic performance.

It is toward such final system testing that the cameras of the Surveyor Lander spacecraft, integral with the spacecraft, would be guided by engineers familiar with these well established test standards. Each subsystem test would then, of course, be a planned step toward the final system performance testing, conducted for cartographic cameras which must operate under large ranges of environment. For the photogrammetric engineer it would be logical to establish the details of subassembly performance based upon well-conceived, if not written, requirements and procedures of a systems test. The following two methods of alignment and calibration fit this category, and are offered as such. The methods are based upon the use of simple equipment and standard measuring and alignment techniques modified only to fit the output of the vidicon tube to supply photogrammetric information, and the physical limitation and assembly of parts peculiar to the Surveyor Lander spacecraft design.

While either method may be used, it is suggested that both methods be used. In this way, the geometric characteristics of the electronic drive and linearity of scanning may be most nearly separated from the optical and mechanical characteristics.

4.5.1 Discussion of the Principal Point and Suggested Calibration of the Completed Vidicon Camera

Principal Point

The principal point of autocollimation is the most stable point from which to make photogrammetric measurements when it is defined and obtained in accordance with accepted standard procedure. Its location cannot, however, be transferred from one lens test to another unless the lens and focal plane are a rigid assembly with respect to one another and fixed rigid fiducial references are available. Such a lens can then also be defined as a lens cone. This description does not fit the Variable Focal Length Lens Assembly since the focal plane lies on the inner surface of the vidicon face plate and when tests are made a simulated face plate is provided.

Final lens test data should therefore be considered only as a measurement of the acceptability of the product, and final calibration data should be obtained when the camera is completely assembled. Since the assymmetric characteristics of the lens as it is installed in the camera is required, an adequately precise method for final testing must be set up with each step of the procedure being carefully detailed. Following the final adjustment of the coordinate axis of the camera, which includes the vidicon tube in position and operating, it is suggested that camera calibration tests be made using a high quality monitor from which photographs can be obtained and on which measurements can be made. This test should be made from a well defined camera station with respect to which photogrammetric targets have been set at known distances and angles. Since the geometric characteristics of the reseau grid have previously been measured, data obtained from the tests will have control similar in form and quality to that which will be obtained under lunar operating conditions. It is suggested the target (or targets) which covers the full field of the 100 mm lens be placed at a distance which provides a scale factor of approximately 100:1. With such a setup the inner orientation elements of each camera could be determined under operating conditions. Tests should be repeated in order that data be adequate to determine the variables of the assembled system.

The results should then be compared to data obtained with the goniometer.

If the reseau is illuminated, the goniometer can be used to read out the angles by which the reseau points are subtended. Following data reduction and if desirable, a point of symmetry can also be obtained by applying the techniques derived by Sewell as shown in the second Manual of Photogrammetry.

It would be desirable to repeat the camera tests using a much smaller scale factor. The 4 ft. minimum distance is suggested as being most informative. The target need only be large enough to cover the full field of the vidicon reseau, and be positioned approximately perpendicular to the lens axis, as seen through the mirror as azimuth zero position.

Results of these two tests will determine the change in the distortion characteristics and repetitive tests between the goniometer calibration at infinity focus and the finite distance test will establish the precision which may be expected of the operating camera under ambient conditions. It is important to consider all the details of such a test in order that it may be also used under environmental conditions to prove the reliability and the operating characteristics of the vidicon camera mounted on the spacecraft and operating under lunar conditions. If, for instance, the results obtained under extremes of temperature showed large and possibly not reputable results, then tests should be extended until that temperature was found at which results were reliable. It might conversely be found that reliability of calibration was a function of temperature and temperature gradient, and with this knowledge, operating programs could be defined and reliability of the output more surely predicted.

4.5.2 Suggestions for Aligning and Testing the Alignment of the Variable Focal Length Vidicon Cameras on the Spacecraft

In order to obtain photogrammetric information after the soft landing on the moon, the orientation of the vidicon cameras with respect to the spacecraft and to one another should be known with a high order of accuracy. An order of the precision of the scanning motion (or the incremental positions of the mirror) should also be obtained. The procedures which finally evolve for making special alignments and calibrations should be very detailed, with carefully computed tolerances established for each camera station. The following programs contain no such details, but offer instead two methods, which have both the virtue of simplicity and of being easily set up at any field laboratory. If these suggested methods are considered feasible, they should be completed with the necessary additional details and tolerances.

A. EQUIPMENT

Method 1: Equipment consists of theodolites, plumb lines, 5 second levels, small optical flats, steel measuring tapes, and 12 to 15 resolution targets with a cross hair target as a fiducial to mark the pointing angle.

Method 2: A goniometer modified to satisfy the physical conditions peculiar to the spacecraft such that the telescope will rotate in a truly horizontal plane around its (non-existent) center, which should be coincident with the front surface of the mirror at the intersection of the azimuth and elevation axes. (It is recognized that physical conditions may make it difficult or impossible for the goniometer to cover the full 360° azimuth range of the camera. However, if more than 180° can be covered, it may be well worth the cost of modifying the goniometer to accomplish what is one of the most important photogrammetric tests.)

B. IDEAL LOCATION OF CAMERAS ON SPACECRAFT

The ideal location of cameras on the spacecraft, and the orientation of the spacecraft axes following alignments, would be as follows:

1) The Z-axis of the spacecraft would be truly vertical, and represented by a structural member whose verticality could be known and measurable within 5 seconds of arc.

2) The focal planes of the cameras as represented by the top surfaces of the vidicon face plates would be truly horizontal. The center line of reseau dots for one camera (the X direction) would be parallel to the center line of dots of the other cameras. The perpendicular lines of dots of the two reseaus would then be parallel to the center line of dots of the other camera, both being parallel to the longest, principal base line between the two cameras. The perpendicular lines of dots of the two reseaus would then be parallel to the Y axis.

C. PROCEDURE

The spacecraft must be set on level terrain or on a level cement block such that the Z-axis can be made vertical by means of adjustments on the spacecraft leveling feet. This can be done by placing a plumb line in close proximity to the structural member representing the Z-axis and tracking the structure and the plumb line simultaneously with the elevation motion of a theodolite. The exact position of the feet should be marked on the terrain or the level cement block such that the spacecraft can be removed and accurately replaced. While the spacecraft is in position, the location of the camera stations must also be established relative to the cement block. This means both the height above the block (parallel to the Z-axis) and the X and Y coordinate positions perpendicular to the Z-axis. These camera stations are the positions on the front surface of the mirror where the azimuth and elevation axes intersect. It will be necessary to mount a theodolite with its rotation point within approximately 1/8" of the center of the camera stations.

D. POSITIONING OF TARGETS FROM THE CAMERA STATION

After the spacecraft has been removed from the block and a theodolite placed at the prime camera station, a minimum of ten targets should be positioned at selected distances and angles from this camera station such that they are a multiple (full unit) of the angular increments between adjacent azimuth positions of the mirror. The fiducial center of these targets should, if possible, be placed on the true horizon with respect to the one (prime) camera station. At at least two positions around the circle additional targets should be placed such that the elevation range is covered and the elevation motion of the camera may be checked. Having placed the targets with respect to the prime station, their positions are read and measured from the second camera station.

E. ALIGNMENT AND CALIBRATION OF CAMERAS

The spacecraft is then replaced on the cement block, and verticality of the Z-axis is rechecked. The focal planes of the cameras, as represented by the front surface of the vidicon tubes, are then made horizontal by whatever means are available. To accomplish this, the cameras should be removed from the spacecraft except for the vidicon tubes. Small levels should be placed on the surface of the tubes, and they should be adjusted (or the whole bearing should be adjusted or shimmed) until the vidicon tube surface is truly horizontal. The camera is then reassembled with its correct adjustments for focus and for principal point as established by previous tests. With the mirror in the 45° position with respect to the plane containing the base line between the two cameras and their optical axes, two theodolites are then set up at approximately the same height as the camera mirrors at distances of approximately 8 feet from the cameras, the distance between the theodolites being equal to the longest base line between the cameras. The positions of the two theodolites and the two cameras will then form a rectangle in the horizontal plane.

During the adjustment phase both theodolites will have been leveled to be horizontal, and both separately autocollimated to be assured of infinity focus. Each theodolite must then be rotated 360°, with leveling continuing until it reads within seconds in a horizontal plane.

Measuring and aligning are then checked. The theodolites are directed toward each other, and when carefully set, the "Zero" position is read. They are then turned exactly 90° to observe the cameras facing them at the end of the base line, while the mirror is adjusted until the line of sight of the theodolite and the reflected optical axis of the camera, as defined by the principal point, are collinear. (Some further adjustment may be necessary at this stage.) The angle between the reseau dots, representing the indicated principal point, and the other reseaus are then read in elevation and in azimuth, and corrected mathematically for reference to the principal point of autocollimation, if the indicated principal point and the principal point of autocollimation, if the indicated principal point and the principal point of autocollimation are not coincident. The line of reseau dots should be parallel to the horizontal or elevation motion of the theodolite. (A light will be necessary to illuminate the reseau dots, but this should be simple to provide.) When reseaus are found to be aligned parallel to each other, or have been adjusted to be parallel as part of this test, the theodolites are removed, and the fully operational cameras are tested.

Targets previously placed at finite distances and known angles from the camera stations are scanned by the cameras, and recorded photographically from the images of the high quality monitor. The input program should be such as to direct the operation of the cameras to obtain calibration information -- resolution and geometry -- for the full field of the lens and for selected positions of the mirrors. The first part of the test can be compared with the optical mechanical goniometer calibration method, and the latter will provide data equivalent to that obtained under working operation.

F. CALIBRATION OF CAMERAS BY GONIOMETER METHOD

In calibrating the cameras by goniometer method, the goniometer is located such that its center is coincident with the intersection of the elevation and azimuth axes of the mirror, the azimuth motion of the telescope being adjusted to ride in a true horizontal plane. Using the indicated principal point of the previously aligned cameras, the angles by which the reseau dots (illuminated by supplementary lamps) are subtended are read by the goniometer. Data is reduced in the same method as detailed in the goniometer method of camera calibration. The goniometer is then rotated to known angles, and the camera mirror is directed to that angle. Deviations in position of the indicated principal point will be read by the goniometer. Any change in quality of the image is also recorded.

G. ENVIRONMENTAL TESTS

The operational tests of the cameras using fixed targets suggested above should be extended in order that the dependability of resolution and the geometric characteristics under specified environments may be determined. Armed with adequate statistical data supplied by such controlled tests it will be possible to best evaluate the reconstructed images which will appear on earth-based equipment of the photographed lunar objects, attaching also a figure of merit to the validity of the information found in the reconstruction.